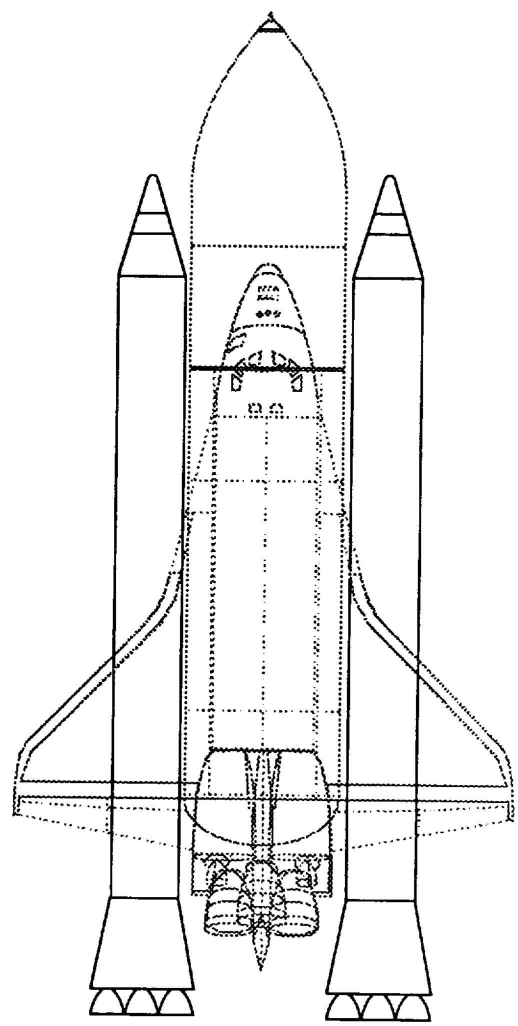
NAS8-37136

March 1989

Appendix D
Trady Study
Summary for the
Liquid Rocket
Booster

Liquid Rocket Booster (LRB) for the Space Transportation System (STS) Systems Study



(NASA-CR-183790-App-D) LIQUID ROCKET BOOSTER (LRB) FOR THE SPACE TRANSPURTION SYSTEM (STS) SYSTEMS STUDY. APPENDIX D: TRADE STUDY SUMMARY FOR THE LIQUID ROCKET BOOSTER (Martin Marietta Corp.) 60 p

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MANNED SPACE SYSTEMS

Trade Study Summary for the Liquid Rocket Booster Study

Appendix D

LRB Trade Studies and Summaries

Avionics Trades Summary

Title	Options	Results	Rationale
Avionics Architecture	Centralized or Distributed Control	Centralized Control for Pump or Pressure	Minimizes Interfaces & Orbiter Impacts
Expendable vs Reusable	Expendable or Reusable Avionics	Expendable Avionics	LCC Cost Advantage Less Than Facilities, Operational Complexity & Maintainability Impacts
Thrust Vector Control	Electromechanical or Hydraulic Actuators or Fluid Injection	Hydraulic Actuators	Least Expensive Avionics, Less Weight, Proven System
Engine Control Electronics	Pump-Fed or Pressure-Fed	Pressure-Fed Engine Control	Less Complex, Fewer Interfaces, Smaller & Less Power
STS Avionics Interfaces	MDM Serial Channels, Orbiter Bus Taps, or Analog/Discrete	Orbiter Bus Taps	Fewer Channels Required, Less Integration Impacts
Software Development	HAL-S, ADA, C or Assembly Language	ADA	Endorsed by NASA & DOD, Highly Structured, Growth Capability

LRB Trade Studies Plan

Discipline: Avionics/Flight Control

Trade No: A-1

Title: Avionics Architecture

Baseline: Centralized Control on LRB (Pump & Pressure-Fed)

Candidates: Distributed Control on LRB (Pump & Pressure-Fed)

Selection Criteria:

Criteria	Weighting Factor	Centralized Control on LRB				Distributed Control on LRB			
		Pump-Fed		Pressure-Fed		Pump-Fed		Pressure-Fed	
		Score	Wghted Score	Score	Wghted Score	Score	Wghted Score	Score	Wghted Score
STS Integration Impacts	25	10	250	10	250	2	50	3	75
DDT&E Costs	10	4	40	5	50	5	50	10	100
Life Cycle Costs	15	7	105	8	120	5	75	10	150
Operational Complexity	10	8	80	10	100	6	60	10	100
Recovery/Reusibility	5	3	15	5	25	5	25	10	50
Safety/Reliability	10	3	30	5	50	5	50	10	100
Growth/Evolution	10	10	100	10	100	3	30	5	50
Weight	5	5	25	8	40	7	35	10	50
Subsystem Integration	10	3	30	5	50	5	50	10	100
	100		675		785		425		775

A-1 Avionics Architecture Summary

STS Integration Impacts

- Centralized Architecture Minimizes Interfaces & Minimizes Orbiter Hardware
- Interfaces : Central Pump - 4, Central Pressure - 4, Distr. Pump - 16, Distr. Press - 12

DDT&E Costs

- Depends on Number of Components, Orbiter Interfaces Not Considered
- LRU Types & SW LRUs : CPump -3 & 8, CPress - 2 & 8, DPump - 2 & 8, DPress - 1 & 4

Life Cycle Costs

- Depends on Production & Operations Counts

Operational Complexity

- Varies with No. of LRUs & I/Fs : CP - 12 & 4, CPr - 8 & 4, DP - 8 & 12, DPr - 4 & 8

Recovery/Reusability

- Inverse Function of LRU Count - Distributed Pressure is Best

Safety/Reliability

- Inverse of LRU Count, Fewer Parts Increase Reliability - Distributed Pressure is Best

Growth/Evolution

- Inverse of I/Fs, Centralized System Does Not Overload Interfaces & Leaves Space for Growth

Weight

- Centralized Systems Are Heavier Due to Added LRUs
- Weights : CP - 680, CPr - 520, DP - 560, DPr - 400

Subsystem Integration

- Function of No. of LRUs - Distributed Pressure is Best

CENTRALIZED CONTROL ARCHITECTURE SHOULD BE MAINTAINED FOR BASELINE CONFIGURATIONS FOR PUMP & PRESSURE-FED LRBs

CENTRALIZED PRESSURE-FED IS BEST OVERALL ARCHITECTURE

LRB Trade Studies Plan

Discipline: Avionics/Flight Control

Trade No: A-2

Title: Expendable vs. Reusable Avionics

Baseline: Expendable Avionics

Candidates: Reusable Avionics

Selection Criteria:

Criteria	Weighting Factor	Expendable Avionics		Reusable Avionics	
		Score	Weighted Score	Score	Weighted Score
Life Cycle Costs	30	7	210	10	300
Launch Facilities/Ground Impacts	20	10	200	9	180
Operational Complexity	10	10	100	6	60
Weight	10	10	100	9	90
Maintainability	10	10	100	6	60
Technical Risks	10	10	100	9	90
Test Requirements	10	10	100	9	90
	100		910		870

A-2 Expendable vs Reusable Avionics Summary

Life Cycle Costs

- Expendable Hardware that Uses Class S Man-Rated Parts Will Cost About the Same
- Production Costs Are Less for Recoverable Due to Quantity Reduction

Launch Facilities/Ground Impacts

- Refurbishment & Retest of Electronics Will Be Minor, Expendable Slightly Better

Operational Complexity

- More Ops Time, Test & Checkout

Weight

- Reusable Parts May Require Stronger Structure, Less than 10% Difference

Maintainability

- Processability, Durability, Spares, Training, & Task Complexity Better for Expendables

Test Requirements

- Additional Quality Tests on Reusable Avionics

Technical Risks

- Reusable Adds Slight Risk of Inadequate Refurbishment

EXPENDABLE RATES SLIGHTLY HIGHER BUT WITH
WITH MAN-RATED AVIONICS FOR BOTH CANDIDATES, EITHER IS ACCEPTABLE

IF CLASS "B" REDUNDANT APPROACH WAS PERMISSIBLE DUE TO SHORT FLIGHT TIME,
EXPENDABLE WOULD BE CLEAR CHOICE DUE TO COST REDUCTION

LRB Trade Studies Plan

Discipline: Avionics/Flight Control

Trade No: A-3

Title: Thrust Vector Control Studies

Baseline: Actuators (Pump), Fluid Injection (Press)

Candidates: Fluid Injection, Hydraulic Actuators, Electromechanical Actuators

Selection Criteria:

Criteria	Weighting Factor	Fluid Injection Avionics		Hydraulic Actuator Avionics		Electromechanical Actuator Avionics	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
DDT&E Costs	10	8	80	10	100	4	40
Life Cycle Costs	20	9	180	10	200	7	140
Performance	10	4	40	10	100	6	60
Operational Complex.	10	10	100	5	50	8	80
Weight	10	10	100	10	100	5	50
Recovery/Reusabilty	10	10	100	10	100	3	30
Safety/Reliability	10	10	100	10	100	3	30
Size	10	10	100	10	100	3	30
Technical Risks	10	8	80	10	100	5	50
	100		880		950		510

A-3 TVC Avionics Summary

DDT&E Costs

- Function of Development : F - 5, H - 10, E - 2
- Function of LRU Types : F - 1, H - 1, E - 2

Life Cycle Costs

- More LRUs for Electromechanical Increases Costs: F - 4, H - 4, E - 12
- Lower DDT&E for Hydraulics

Operational Complexity

- Function of Rqts of Supporting Systems : F - 10, H - 5 (Hydr.), E - 8 (Power)

Performance

- Hydraulics - Proven, Fluid Injection - Limited Gimballing, Electro.- Uncertain, Not Developed

Weight - Avionics Only

- Fluid & Hydraulics - 160 lbs each, Electro. - 320 lbs (Does Not Include Batteries)

Recovery/Reusability

- Electromechanical Has More LRUs to Be Recovered

Safety/Reliability

- Hydraulics Reduces Safety; More LRUs for Electro. Reduces Reliability

Size

- More LRUs for Electro. Increases Size

Technical Risks

- Electromechanical Development Increases Risk
- Fluid Injection Performance Increases Risk

HYDRAULICS TVC IS BEST SOLUTION IN AVIONICS DUE TO MATURITY
FLUID INJECTION TVC CLOSE SECOND WITH PERFORMANCE WEAKNESSS
ELECTROMECHANICAL TVC REQUIRES DEVELOPMENT

LRB Trade Studies Plan

Discipline: Avionics/Flight Control

Trade No: A-4

Title: Engine Control Electronics

Baseline: Pump-Fed Engine

Candidates: Pressure-Fed Engine

Selection Criteria:

Criteria	Weighting Factor	Pump-Fed Engine		Pressure-Fed Engine	
		Score	Weighted Score	Score	Weighted Score
DDT&E Costs	20	9	180	10	200
Life Cycle Costs	20	8	160	10	200
Operational Complexity	20	7	140	10	200
Size/Weight	10	9	90	10	100
Power	10	9	90	10	100
Safety/Reliability	20	9	180	10	200
	100		840		1000

A-4 Engine Control Trade Summary

DDT&E Costs

- Input/Ouput Rqts of Pressure Are 67% of the Pump, Total Card Count for Pressure Is 88% of the Pump Making Pressure Less Costly

Life Cycle Costs

- Operational Costs Are Lower for Pressure Due to Fewer Interfaces

Operational Complexity

- Pump I/Fs - 198 , Pressure I/Fs 133 ; Pressure Less Complex

Size/Weight

- Pump - 180 lbs each, Pressure - 155 lbs

Power

- Pump - 350 watts, Pressure - 328 watts

Safety/Reliability

- Inverse Function of Card Count : Pump - 43, Pressure - 38 ; Pressure Best

PRESSURE-FED ENGINE CONTROL REQUIREMENTS SATISFIED BY MORE MODEST CONTROLLER

LRB Trade Studies Plan

Discipline: Avionics/Flight Control

Trade No: A-5

Title: STS Avionics Interfaces

Baseline: MDM Serial Channels

Candidates: Orbiter Bus Taps, Analog/Discrete

Selection Criteria:

Criteria	Weighting Factor	MDM Serial Bus		Orbiter Bus		Analog/Discrete	
		Score	Wgt Score	Score	Wgt Score	Score	Wgt Score
STS Integration Impacts	20	8	160	10	200	5	100
DDT&E Costs	10	10	100	9	90	7	70
Life Cycle Costs	20	8	160	10	200	6	120
Operational Complexity	10	8	80	10	100	2	20
Technical Risks	10	10	100	10	100	6	60
Safety/Reliability	10	8	80	10	100	2	20
Subsystem Integration	10	8	80	10	100	1	10
Growth/Evolution	10	8	80	10	100	5	50
	100		840		990		450

A-5 STS Avionics I/Fs Trade Summary

<u>STS Integration Impacts</u>

- Wiring Interfaces: MDM Serial Bus - 16 channels, Orbiter Bus - 4 channels, A/D - 300+ channels
- MDM Serial Bus Causes Slight Transport Delay
- Orbiter Hardware: MDM Serial Bus-4 cards, Orbiter Bus-4 Transformers, A/D-4 MDMs & connectors
- Orbiter Software: MDM Serial Bus - GPC s/w, Orbiter Bus - GPC & BUS, A/D - GPC & BUS

<u>DDT&E Costs</u>

- Function of Hardware & Software Mods - Therefore MDM Serial Bus is Best

<u>Life Cycle Costs</u>

- Production: MDM Serial Bus - Card & Orbiter Interface Assy (OIA), Orbiter Bus - OIA, A/D - MDM
- More I/Fs for A/D Increases LCC

<u>Operational Complexity</u>

- Function of LRUs & I/Fs - Therefore A/D Rates Lowest

<u>Technical Risk</u>

- Transport Delay for MDM Serial Bus, Bus Architecture Mod for New Taps, & Added I/F Count for A/D

<u>Safety/Reliability</u>

- Component Count Decreases Reliability
- MDM Serial Bus - 4 cards, Orbiter Bus - 4 taps, A/D - MDM & connectors

<u>Subsystem Integration</u>

- Interfaces Increases Integration: MDM Serial Bus - 16, Orbiter Bus - 4, A/D - 300+

ORBITER BUS TAPS IS BEST SOLUTION FOR LRB AVIONICS I/F FOLLOWED CLOSELY BY MDM SERIAL BUS. ANALOG/DISCRETE WOULD REQUIRE ORB/ET/LRB CABLING.

LRB Trade Studies Plan

Discipline: Avionics/Flight Control

Trade No: A-6

Title: Software Development Concepts

Baseline: HAL-S for Orbiter, ADA for LRB

Candidates: HAL-S, ADA, Assembly Language, & C

Selection Criteria:

Criteria	Weighting Factor	HAL-S		ADA		Assy Language		C	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
STS Integration Impacts	20	5.5	110	9.4	188	5.0	100	10.0	200
DDT&E Costs	20	4.3	86	10.0	200	4.1	82	9.0	180
Technical Risks	20	4.6	92	10.0	200	5.1	102	9.6	192
Safety/Reliability	20	5.4	108	10.0	200	6.8	136	9.6	192
Subsystem Integration	10	3.0	30	10.0	100	6.1	61	9.4	94
Test Requirements	10	4.2	42	10.0	100	4.5	45	9.2	92
	100		468		988		526		950

A-6 Software Development Concepts Summary

STS Integration Impacts

- Memory is limited resource, efficient code generator provides margin : C is best code generator
- Integration easier with SW that accommodates growth : ADA is best, Assy not designed for growth

DDT&E Costs

- Structured language reduces cost : ADA is highly structured, C is good, Assy is not structured
- Real time features reduce cost : Assy & C are best, HAL-S not extensively used for real time
- Maturity improves cost : Assy & C are most mature, HAL-S mature but only for Shuttle
- Commonality with GFE & vendor base : ADA designed for commonality, others are not
- Growth reduces cost from late rqts : ADA is best because independent of arch. & ops system
- Flexibility reduces costs during design : ADA & C are highly flexible, Assy is not
- Computer test equip allows C/O to reduce costs : ADA & C on mini & micro, HAL-S STS GPC only
- Documentation & development tools reduce costs : ADA has best set of tools

Technical Risks

- Risks are reduced by structured languages, maturity, commonality, flexibility and development tools; ADA & C have lowest risks

Safety/Reliability

- Safety/reliability increases with structured languages, real time features, efficient code generation, maturity, growth & commonality ; ADA & C have best of these traits

Subsystem Integration

- ADA & C have best characteristics for integration - real time, efficient code, growth, test equip, etc.

Test Requirements

- ADA is best due to documentation & development tools & test equipment

ADA & C ARE CLEAR LEADERS: ADA IS PREFERRED BECAUSE OF ITS ENDORSEMENT BY NASA & DOD; INVESTMENT BY SUBCONTRACTORS, VENDORS, DOD & NASA; NATIONAL STANDARD; RAPID DEVELOPMENT & CERTIFICATION PROCESS.

Propulsion Trades Summary

Title	Options	Results	Rationale
Pump-Fed Propellants	N2O4/MMH, LO2/RP-1, LO2/CH4	LO2/RP-1	Lowest Cost, Safest, Low Environmental Impacts
Pressure-Fed Propellants	N2O4/MMH, LO2/RP-1, LO2/CH4, LO2/C3H8, N2O4/ALMMH	LO2/RP-1	Lowest Cost, Safest, Low Environmental Impacts
Pressurization System Study - N2O4/MMH	ScHe/Hx/GG, ScHe-LH2/2Hx/GG, ScHe/Hx/High Pc GG, ScHe/Stoich GG, ScHe/Stoich GG/TPA	ScHe/Hx/GG	Lowest Cost, Least Complex/ More Reliable, Low Technical Risks
Pressurization System Study - LO2/RP-1	ScHe/Hx/GG, ScHe-LH2/2Hx/GG, ScHe-LH2 Stoich GG, ScHe-LH2/Stoich GG/TPA, ScHe/Stoich GG/TPA	ScHe/Hx/GG	Lowest Cost, Least Complex/ More Reliable, Low Technical Risks
Thrust Vector Control	Gimbals or Liquid Injection	Gimbals	Less Expensive, Less Weight/ More Performance, MoreReliable
TVC Gimbals	Hydraulic or Electromechanical	Electromechanical	Less Expensive, Less Complex/ More Reliable, Safer, Less Wgt
Expendable vs Reusable Propulsion for Pump-Fed	Expendable or Reusable Engines	Reusable Engines	LCC Advantage
Expendable vs Reusable Propulsion for Pressure-Fed	Expendable or Reusable Engines	Expendable Engines	Less Complex System, Fewer Facilities/Ground Impacts, Less Supportability

LRB Trade Studies Plan

Discipline: Propulsion

Trade No: P-1

Title: Propellant Trades

Baseline: N2O4/MMH

Candidates: N2O4/ALMMH, LOX/RP-1, LOX/CH4, LOX/C3H8

Selection Criteria:

Criteria	Wgting Factor	PUMP-FED						PRESSURE-FED									
		N2O4/MMH		LOX/RP-1		LOX/CH4		N2O4/MMH		LOX/RP-1		LOX/CH4		LOX/C3H8		N2O4/ALMMH	
		Sc	Wgt Sc	Sc	Wgt Sc	Sc	Wgt Sc	Sc	Wgt Sc	Sc	Wgt Sc	Sc	Wgt Sc	Sc	Wgt Sc	Sc	Wgt Sc
STS Integration Impacts	15	10	150	7	105	6	90	9	135	6	90	5	75	6	90	10	150
Costs	10	7	70	10	100	10	100	1	10	10	100	8	80	10	100	1	10
Operational Complexity	5	10	50	10	50	8	40	10	50	10	50	8	40	8	40	8	40
Safety	15	2	30	10	150	8	120	2	30	10	150	8	120	9	135	1	15
Reliability	5	10	50	9	45	8	40	10	50	9	45	4	20	4	20	5	25
Weight	5	8	40	7	35	10	50	8	40	9	45	7	35	10	50	10	50
Maintainability	5	10	50	6	30	7	35	10	50	6	30	6	30	6	30	7	35
Subsystem Integration	5	10	50	9	45	8	40	10	50	9	45	8	40	8	40	10	50
Facility Impacts	15	10	150	9	135	8	120	9	135	7	105	6	90	6	90	7	105
Env. Impacts	15	4	60	9	135	10	150	4	60	9	135	10	150	10	150	4	60
Risks (Sched. & Tech.)	5	10	50	7	35	9	45	10	50	7	35	6	30	5	25	2	10
	100		750		865		830		660		830		710		770		550

P-1 Propellant Trades Summary

STS Integration Impacts

- Propellants Increase Size of Booster which Increases Orbiter Wing Loads
- Pump Fed Boosters: N2O4/MMH - 14.5' x 150', LOX/RP-1 - 15.3' x 151', LOX/CH4 - 16.1' x 152'
- Press Fed Boosters: N2O4/MMH - 15.6' x 157', LOX/RP-1 - 16.7' x 158', LOX/CH4 - 19.3' x 154', LOX/C3H8 - 17.1' x 156', N2O4/ALMMH - 13.9' x 154'
- Propellants Affect Launch Area Environments: N2O4/ALMMH Creates Launch Stand Convective Env. More Severe than SRB, LOX/RP-1 Creates More Severe Base Rad. Env. to the LRB, Orb & ET
- Double Cryo Tanks Impose Greater ET/LRB Structural Interface Loads

Costs

- Pump - Fuel & Oxidixer Costs & Safety Costs Much Higher for N2O4/MMH
- Pressure - Fuel & Oxidizer Costs, Safety Costs, Operational Costs, & Transportation Costs Are Much Higher for N2O4/MMH
- Oxidizers: N2O4 - $1.75/lb, LOX - $.04/lb
- Fuels: MMH - $10.00/lb, RP-1 - $.21/lb, CH4 - $.71/lb, C3H8 - $.27/lb
- Engines: Pump-Fed Engines Less Expensive for Storables, Press-Fed Same Across All Propellants

Operational Complexity

- Storable Require SCAPE, Serial Loading Required, No T-0 Umbilicals
- Cryogenics Require TPS Closeouts & T-0 Umbilicals, LOX Procedures Already Developed

Safety

- Storables Are Highly Toxic, Corrosive to Skin & Eyes, SCAPE Required, Highly Reactive, Transportation Is Restricted
- Cryos May Cause Cryogenic Burns
- Propane - Heavier & May Travel Distances to Ignition Source, Narcotic Depressant, Asphiyxiation Hazard
- Methane - Inactive Biologically & Simple Asphyxiant, May Reach Hazardous Levels w/o Symptoms

Maintainability

- N2O4/MMH Requires Little Support Activities, Others Require Supply Support, Maint. Concepts, Personnel Training, & Task Complexity

P-1 Propellant Trades Summary (Cont'd)

Reliability

- Cryos Increase Ops Complexity & Take Larger Volumes
- N_2O_4/ALMMH Poses Engine Chamber Reliability Problems
- N_2O_4/MMH & LOX/RP-1 Are Proven Propellants

Weight

- Propellant Quantity Rqts Vary with Isp & Density, Larger Tank Rqts Increase Structural Wgts
- Pump GLOW : LOX/CH_4 - 853K, N_2O_4/MMH - 981K, LOX/RP-1 - 1001K
- Pressure GLOW : LOX/C_3H_8 - 1250K, N_2O_4/ALMMH - 1256K, LOX/RP-1 - 1318K, N_2O_4/MMH - 1346K, LOX/CH_4 - 1413K

Subsystem Integration

- Cryos Increase Integration Complexity

Facility Impacts

- N_2O_4/MMH - Fuel Handling Air Impacts
- RP-1 - Not Available at Pad, Must Install Capability
- CH_4 - No Facilities/Capabilities at Either Pad

Environmental Impacts

- N_2O_4/MMH - Hypergolic, Storage & Handling Precautions Extensive, Hazardous Wastes Sent Offsite, Permits Required, Extensive Evacuation Plan, Neutralization Scrubbers
- LOX/RP-1 - Non-Hypergolic, Storage & Handling Less Extreme, Simple Absorber Scrubbers for RP, Waste Incenerated Onsite
- LOX/CH_4 & LOX/C_3H_8 - Non-Hypergolic, Simple Absorbers for CH_4 & C_3H_8, Small Evacuation Area

Technical & Schedule Risks

- ALMMH Involves Technology Risk Due to Engine Chamber Problems & Propellant Development
- N_2O_4/MMH - Schedule Risk Due to One Propellant Manufacturer

LOX/RP-1 PROPELLANTS SHOULD BE BASELINED FOR PUMP & PRESSURE-FED LRBs

LRB Trade Studies Plan

Discipline: Propulsion

Trade No: P-2A

Title: Pressurization Systems Study For N2O4/MMH Propellant

Baseline: SC He/HX/Low Pc GG

Candidates: SC He-LH2/2HX/Low Pc GG, SC He/HX/High Pc GG (Fuel Tank Dump), SC He/Stoich GG (N2O4/MMH), SC He/Stoich GG (N2O4/MMH)/TPA

Selection Criteria:

Criteria	Wghting Factor	SC He/HX/GG		SC He-LH2/2HX/GG		SC He/HX/High Pc GG		SC He/Stoich GG		SC He/Stoich GG/TPA	
		Score	Wghted Score	Score	Wghted Score	Score	Wghted Score	Score	Wghted Score	Score	Wghted Score
Costs	20	10	200	8.4	168	8.4	168	4	80	6.1	122
Operational Complexity	10	10	100	8	80	8	80	6	60	4	40
Safety	10	10	100	6	60	8	80	3	30	1	10
Reliability	10	10	100	7	70	8	80	5	50	5	50
Weight	10	8	80	10	100	9	90	6	60	7	70
Subsystem Integration	10	9	90	8	80	9	90	10	100	10	100
Facility Impacts	10	10	100	9	90	10	100	10	100	10	100
Technical Risks	10	10	100	9	90	10	100	7	70	7	70
Supportability	10	10	100	7	70	1	10	1	10	10	100
	100		970		808		798		560		662

P-2A Press. System (N_2O_4/MMH) Summary

Costs

- Components Increase Costs - Extra Heat Exchangers, Tanks, Bottles, Etc.
- Gas Generator Data Not Available But Considered Expensive for High Press. & Stoich.
- Option 4 Requires 3 Tanks & Stoich. GG which Increases Costs

Operational Complexity

- More Components Increase Complexity, Turbopumps Increase Complexity

Safety

- Cryogenic LH_2 Adds Hazards
- Adding Heated Reactants to Hydrazine Creates Added Hazards
- Gas Generators Pose Problem of Dumping Incompletely Oxidized Reactant into Oxidizer Tank
- Turbopumps Further Complicate & Add Failure Modes

Reliability

- More Components in Series Decrease Reliability, Critical Components Like GGs & Stoich. Gas Generators Add Complexity which Decreases Reliability

Weight

- Option 1 - 31.5k, Option 2 - 25.7k, Option 3 - 27.7k, Option 4 - 34.6k, Option 5 - 33.6

Subsystem Integration

- Concepts that Require Heat Exchangers Increase Integration
- Addition of Extra Pressurants Like LH_2 Adds to Integration Concerns

Facility Impacts

- Addition of LH_2 Adds Facility Impacts

Technical Risks

- Stoich. Gas Generators Is High Development Risk Item - Material Survivability, Mixing & Cooling

Supportability

- Options 4 & 5 Require High Processability & Maintenance

FUEL RICH GG FED BY MAIN TANKS THAT PROVIDES HEAT TO SUPERCRITICAL HELIUM VIA A PLATELET HEAT EXCHANGER SHOULD BE THE PRESSURIZATION SYSTEM

LRB Trade Studies Plan

Discipline: Propulsion

Trade No: P-2B

Title: Pressurization Systems Study For LO2/RP-1 Propellant

Baseline: SC He/HX/Low Pc GG

Candidates: SC He-LH2/2HX/Low Pc GG, SC He-LH2 Stoich GG (LO2/LH2), SC He-LH2/Stoich GG (LO2/LH2)/TPA, SC He/Stoich GG (LO2/RP1)/TPA

Selection Criteria:

Criteria	Wghting Factor	SC He/HX/GG		SC He-LH2/2HX/GG		SC He-LH2 Stoich GG		SC He-LH2 /Stoich GG/TPA		SC He/Stoich GG/TPA	
		Score	Wghted Sc	Score	Wghted Sc	Score	Wghted Sc	Score	Wghted Sc	Score	Wghted Sc
Costs	20	10	200	9.6	192	5	100	8	160	8.6	172
Operational Complexity	10	10	100	8	80	6	60	6	60	6	60
Safety	10	10	100	6	60	5	50	3	30	1	10
Reliability	10	10	100	7	70	5	50	5	50	5	50
Weight	10	5	50	7	70	8	80	10	100	7	70
Subsystem Integration	10	9	90	8	80	9	90	10	100	10	100
Facility Impacts	10	10	100	9	90	10	100	10	100	10	100
Technical Risks	10	10	100	10	100	5	50	5	50	5	50
Supportability	10	10	100	5	50	4	40	4	40	4	40
	100		940		792		620		690		652

P-2B Press. System (LOX/RP-1) Summary

Costs
- More Components Increase Costs - Heat Exchangers, Tanks, Bottles, Etc.
- Cost Data for Gas Generator Not Available - Assumed Expensive for Stoich. & High Press.
- Option 3 Requires a Second Large Helium Tank which Increases Cost

Operational Complexity
- More Components Increase Complexity, Turbopumps Increase Complexity

Safety
- Cryogenic LH2 Adds Hazards
- Adding Heated Reactants to Hydrazine Creates Added Hazards
- Gas Generators Pose Problem of Dumping Incompletely Oxidized Reactant into Oxidizer Tank
- Turbopumps Further Complicate & Add Failure Modes
- Press. Fuel & Oxidizer with LOX/RP1 Reaction Products like CO Creates Hazard in LO2 Tank & Nitrous Oxide Creates Hazard in Fuel Tank

Reliability
- More Components in Series Decrease Reliability, Critical Components Like GGs & Stoich. Gas Generators Add Complexity which Decreases Reliability

Weight
- Option 1 - 43.2k, Option 2 - 38.2k, Option 3 - 36.9k, Option 4 - 25.9k, Option 5 - 38.2

Subsystem Integration
- Concepts that Require Heat Exchangers Increase Integration
- Addition of Extra Pressurants Like LH2 Adds to Integration Concerns

Facility Impacts
- Addition of LH2 Adds Facility Impacts

Technical Risks
- Stoich. Gas Generators Is High Development Risk Item - Material Survivability, Mixing & Cooling

Supportability
- All Options Except 1 Require More Processability, Maintenance & Training

FUEL RICH GG FED BY MAIN TANKS THAT PROVIDES HEAT TO SUPERCRITICAL HELIUM VIA A PLATELET HEAT EXCHANGER SHOULD BE THE PRESSURIZATION SYSTEM

LRB Trade Studies Plan

Discipline: Propulsion

Trade No: P-5

Title: TVC

Baseline: Liquid Injection

Candidates: Gimbals (Hydraulic)

Selection Criteria:

Criteria	Weighting Factor	LITVC		Gimbals	
		Score	Weighted Score	Score	Weighted Score
STS Integration Impacts	20	10	200	8	160
Costs	25	7.5	188	10	250
Operational Complexity	25	9	225	10	250
Reliability	10	6	60	10	100
Weight	10	1	10	10	100
Performance	10	5	50	10	100
	100		733		960

P-5 TVC Trade Summary

STS Integration Impacts

- Liquid Injection Requires Additional Plumbing & Propellants Which Impacts Integration
- Gimbals Require More Room in Aft Skirt Area to Allow for Gimbaling Maneuvers

Costs

- Valves Drive LiTVC Costs
- Total Cost/LRB: LiTVC - $1769K, Hydraulic - $1604K

Operational Complexity

- Less Ground Operational Checkout Is Required for Liquid Injection, More for Gimbals
- LiTVC More Complicated for Flight Ops - Multiple Valves Increase Complexity

Reliability

- Liquid Injection Less Reliable Due to More Plumbing & Valves Required

Weight

- Liquid Injection - 17,500 lbs
- Gimbals - Hydraulic - 1300 lbs

Performance

- Weight Penalty of 16,000 lbs Turns into 4800 Lbs/Flt Payload Penalty

GIMBALS SHOULD BE USED FOR TVC

LRB Trade Studies Plan

Discipline: Propulsion

Trade No: P-6

Title: Thrust Vector Control Gimbals

Baseline: Hydraulic Cylinders

Candidates: Lead Screw/Electrical Motor

Selection Criteria:

Criteria	Wgting Factor	Hydraulic Cyl		Lead Screw/Elec Motor	
		Score	Weighted Score	Score	Weighted Score
STS Integration Impacts	10	10	100	9	90
Costs	20	4	80	10	200
Operational Complexity	20	6	120	10	200
Safety	10	4	40	10	100
Reliability	5	5	25	10	50
Weight	10	9	90	10	100
Subsystem Integration	10	10	100	7	70
Technical Risks	10	10	100	6	60
Supportability	5	7	35	10	50
	100		690		920

P-6 TVC Gimbals Trade Summary

STS Integration Impacts

- Electric Requires Battery Cart Hookup for Power
- Response Time Unknown for Electric

Costs

- Actuator Costs Assumed to Be Equal Between Options
- Hydraulic Power Units Drive Costs
- Total Unit Cost/LRB: Hydraulics - $3.4M, Electric - $1.3M

Operational Complexity

- Hydraulics Require Fluid/Fill/Leak Checks, GSE Panels & Tubing, Removal/Replacement Is Complicated
- Electric Has Faster Automatic Checkout, Minimal GSE, & Easier Replacement

Safety

- Hydraulics Require Pump & Plumbing & Needs Lock to Prevent Uncontrolled Gimbaling in the Event of Power Failure

Reliability

- Hydraulics Require Pump & Plumbing which Are Suseptible to Leaks & Subsequent Loss of Power which Could Cause Uncontrolled Gimbaling or Failure to Provide Gimbal Lock

Weight

- Hydraulics - 1300 lbs
- Electric - 750 lbs

Subsystem Integration

- Avionics Impacts Are Greater for Electric

Technical Risks

- Electric Has Not Been Proven & Considered Developmental

Supportability

- Hydraulics Requires More Maintenance & Training & More Spares

LEAD SCREW/ELECTRIC MOTOR SHOULD BE SELECTED FOR TVC ACTUATORS

LRB Trade Studies Plan

Discipline: Propulsion

Trade No: P-8A

Title: Expendable vs. Reusable Propulsion (Pump-Fed)

Baseline: Expendable

Candidates: Reusable

Selection Criteria:

Criteria	Weighting Factor	Expendable		Reusable	
		Score	Weighted Score	Score	Weighted Score
Costs	50	6	300	10	500
Launch Facilities/Ground Impacts	10	10	100	7	70
Operational Complexity	10	10	100	7	70
Weight	5	10	50	9	45
Maintainability	10	10	100	2	20
Test Requirements	10	10	100	8	80
Safety	5	10	50	5	25
	100		800		810

P-8A Exp. vs Reuse. Propulsion (Pump) Summary

Costs
- Engine Refurb Is 30% of Total Engine Costs; 93% Refurb Learning Curve
- Service Life of 10 Flights/Engine
- Engine LCC: Expendable - $5.0B, Reusable - $3.0B

Launch Facilities/Ground Operations
- Reusable Requires Refurb Facilities, Additional GSE & Ground Ops Time for Recovery
- Reusable Requires More Complicated Checkout, Tests, & Software Rqts

Operational Complexity
- Reusable Requires More Ground Operational Complexity
- Reusable Engine Needs More Instrumentation & Controller Has Increased Capacity for Health Monitoring

Weight
- Pump-Fed Engine TPAs Larger (2-5%): Bearings, Turbine & Gas Generator

Maintainability
- Reusable Requires More Processability (Time, Facilities, Experience), More Spares, Personnel, Training & Maintenance

Test Requirements
- No. of Engine Tests Required: Expendable - 900, Reusable - 1000

Safety
- Safety/Reliability Remains the Same During Flight
- Reusable Requires Recovery which Involves Hazards of Seas, Ships, Possible Hazardous Materials

REUSABLE ENGINES FOR PUMP-FED LRB SHOWS PROMISE
NEED MORE DETAILS TO MAKE FINAL DECISION

LRB Trade Studies Plan

Discipline: Propulsion

Trade No: P-8B

Title: Expendable vs. Reusable Propulsion (Pressure-Fed)

Baseline: Expendable

Candidates: Reusable

Selection Criteria:

Criteria	Weighting Factor	Expendable		Reusable	
		Score	Weighted Score	Score	Weighted Score
Costs	50	8	400	10	500
Launch Facilities/Ground Impacts	10	10	100	7	70
Operational Complexity	10	10	100	7	70
Weight	5	10	50	10	50
Maintainability	10	10	100	2	20
Test Requirements	10	10	100	10	100
Safety	5	10	50	5	25
	100		900		835

P-8B Exp. vs Reuse. Propulsion (Press) Summary

<u>Costs</u>
- Engine Refurb 50% of Total Engine Costs; 93% Refurb Learning Curve
- Service Life of 15 Flights/Engine
- Engine LCC: Expendable - $3.3B, Reusable - $2.6B

<u>Launch Facilities/Ground Operations</u>
- Reusable Requires Refurb Facilities, Additional GSE & Ground Ops Time for Recovery
- Reusable Requires More Complicated Checkout, Tests, & Software Rqts

<u>Operational Complexity</u>
- Reusable Requires More Ground Operational Complexity
- Reusable Engine Needs More Instrumentation & Controller Has Increased Capacity for Health Monitoring

<u>Weight</u>
- Weights Similar Between Expendable & Reusable

<u>Maintainability</u>
- Reusable Requires More Processability (Time, Facilities, Experience), More Spares, Personnel, Training & Maintenance

<u>Test Requirements</u>
- No. of Tests Similar for Exp. vs Reusable

<u>Safety</u>
- Safety/Reliability Remains the Same During Flight
- Reusable Requires Recovery which Involves Hazards of Seas, Ships, Possible Hazardous Materials

LRB PRESSURE-FED ENGINES SHOULD REMAIN EXPENDABLE

Recovery Trades Summary

Title	Options	Results	Rationale
Pump-Fed Expendable vs Recoverable	Totally Expendable, Partially Recoverable, or Totally Recoverable	Totally Expendable	Less Complex, Less Weight/More Performance, Less Operations Impact, Less Facilities Impact
Pressure-Fed Expendable vs Recoverable	Totally Expendable, Partially Recoverable, or Totally Recoverable	Totally Expendable	Less Complex, Less Weight/More Performance, Less Operations Impact, Less Facilities Impact

LRB Trade Studies Plan

Discipline: Recovery

Trade No: R-1A

Title: Expendable vs. Recoverable (Pump-Fed)

Baseline: Totally Expendable Vehicle

Candidates: Totally Recoverable Vehicle, Partially Recoverable Vehicle

Selection Criteria:

Criteria	Weighting Factor	Expendable		Totally Recoverable		Partially Recoverable	
		Score	WgtScore	Score	WgtScore	Score	WgtScore
Costs	45	7	315	9	405	10	450
Performance	5	10	50	8	40	9	45
Launch Facilities/Ground Impacts	10	10	100	5	50	6	60
Operational Complexity	10	10	100	5	50	6	60
Weight	5	10	50	7	35	8	40
Maintainability	10	10	100	6	60	6	60
Safety	5	10	50	5	25	5	25
Test Requirements	10	10	100	5	50	5	50
	100		865		715		790

R-1A Exp. vs Recoverable (Pump) Summary

Costs
- 20% LCC Delta Between Expendable & Partially Recoverable
- Pump-Fed Engines Good Candidates for Recovery - Engine Cost Advantage Minimized by Refurbishment & Recovery Costs

Launch Facilities/Ground Impacts
- Recoverable Requires Refurb Facilities, GSE, Recovery Ships, Etc.
- Recoverable Has More Complicated Checkout, Tests, & Software Rqts

Operational Complexity
- Recoverable Requires Pyrotechnics, Parachutes, Retro Rockets, Flotation, Instrumentation, Etc. which Increases Complexity
- Ground Operations More Involved for Recoverable System

Weight (Recovery System)
- Totally Recoverable - 8394 lbs
- Partially Recoverable - 3147 lbs

Maintainability
- Recoverable Systems Require Spares, Maintenance, Processing, & Training

Test Requirements
- Recoverable Systems Require Drop Tests to Verify Designs

Performance
- Weight Penalty for Recovery System Means Payload Penalty of 944 lbs/flight for Partially Recoverable & 2518 lbs/flight for Totally Recoverable

Safety
- Recoverable Introduces Hazards of Ships, Seas, & Possible Recovery of Hazardous Material

PUMP-FED LRB SHOULD BE EXPENDABLE

LRB Trade Studies Plan

Discipline: Recovery

Trade No: R-1B

Title: Expendable vs. Recoverable (Press-Fed)

Baseline: Totally Expendable Vehicle

Candidates: Totally Recoverable Vehicle, Partially Recoverable Vehicle

Selection Criteria:

Criteria	Weighting Factor	Expendable		Totally Recoverable		Partially Recoverable	
		Score	WgtScore	Score	WgtScore	Score	WgtScore
Costs	45	8	360	9	405	10	450
Performance	5	10	50	6	30	9	45
Launch Facilities/Ground Impacts	10	10	100	5	50	6	60
Operational Complexity	10	10	100	5	50	6	60
Weight	5	10	50	4	20	8	40
Maintainability	10	10	100	6	60	6	60
Safety	5	10	50	5	25	5	25
Test Requirements	10	10	100	5	50	5	50
	100		910		690		790

R-1B Exp. vs Recoverable (Press) Summary

Costs

- 10% LCC Delta Between Expendable & Partially Recoverable
- Pressure-Fed Engines Not Good Candidates for Refurbishment

Launch Facilities/Ground Impacts

- Recoverable Requires Refurb Facilities, GSE, Recovery Ships, Etc.
- Recoverable Has More Complicated Checkout, Tests, & Software Rqts

Operational Complexity

- Recoverable Requires Pyrotechnics, Parachutes, Retro Rockets, Flotation, Instrumentation, Etc. which Increases Complexity
- Ground Operations More Involved for Recoverable System

Weight (Recovery System)

- Totally Recoverable - 30,238 lbs
- Partially Recoverable - 3,994 lbs

Maintainability

- Recoverable Systems Require Spares, Maintenance, Processing, & Training

Test Requirements

- Recoverable Systems Require Drop Tests to Verify Designs

Performance

- Weight Penalty for Recovery System Means Payload Penalty of 1198 lbs/flight for Partially Recoverable & 9072 lbs/flight for Totally Recoverable

Safety

- Recoverable Introduces Hazards of Ships, Seas, & Possible Recovery of Hazardous Material

PRESSURE-FED LRB SHOULD BE EXPENDABLE

Structural/Mechanical Trades Summary

Title	Options	Results	Rationale
Common Bulkhead	Separate Domes or Common Fuel/Oxidizer Bulkhead	Separate Domes	Less Expensive, Easier to Manufacture, Safer
FWD ET/LRB Attachment	Crossbeam or Ring Frame	Crossbeam	Less Expensive, Easier to Manufacture, Less Weight
Dome Optimization	Elliptical or Hemispherical Domes	Hemispherical Domes	Less Expensive, Easier to Manufacture, Less Weight
Unpressurized Structure Construction	Hat-Stiffened, Waffle, Z-Stiffened, Monocoque or Truss Core	Hat-Stiffened	Least Expensive, Easy to Manufacture
Cryo Tank Location	Forward or Aft	Forward	No ET Loads Impacts, No Weight/Performance Penalty
Tank Wall Design	Machined Integral Stiffeners or Thick Wall (Monocoque)	Thick Wall (Monocoque)	Less Expensive, Easier to Manufacture, Less Supportability
Pressure-Fed Tank Materials	Weldalite, 2219 Al, 2090-T8E41, HP 9-4-30	Weldalite	Least Weight/Most Performance
Pump-Fed Tank Materials	Weldalite, 2219 Al, 2090-T8E41, HP 9-4-30	Weldalite	Least Weight/Most Performance
Aft Skirt & Tie Down Attachment	Skin/Stringer or Monocoque	Skin/Stringer	Less Expensive, Easy to Manufacture, Less Weight
Filament Wound Composite Tank	Welded (Weldalite), Filament Wound (Gr/Pk), or Composite Overwrap	Welded (Weldalite)	Least Technical Risks, Safest, Best Supportability

LRB Trade Studies Plan

Discipline: Structures

Trade No: S-1

Title: Common Bulkhead (Pump Only)

Baseline: Separate Tank Domes

Candidates: Common Oxidizer/Fuel Bulkhead

Selection Criteria:

Criteria	Weighting Factor	Separate Domes		Common Bulkhead	
		Score	Weighted Score	Score	Weighted Score
Costs	20	10	200	7	140
Manufacturing Complexity	20	10	200	4	80
Operational Complexity	10	10	100	8	80
Weight	10	5	50	10	100
Reliability	5	10	50	5	25
Safety	20	10	200	5	100
Supportability	5	10	50	4	20
Performance	10	6	60	10	100
	100		910		645

S-1 Common Bulkhead Trade Summary

Costs

- Materials cost is less for common dome due to elimination of Intertank
- Labor-intensive fit up & match operations for common dome
- NDE test of common dome more difficult; leak detection is more difficult
- Common dome has difficult weld set-up & bonding TPS to domes is difficult
- 3 additional dome assys required for testing of common domes
- Additional design effort required for common dome; tooling is more complex

Manufacturing Complexity

- Common bulkhead (double wall construction) requires large diameter flow spun dome development. Common double wall requires accurate dome to honeycomb fitup for bonding. Fitup & match machining of honeycomb for welded panel domes would be too labor intensive at LRB quantities. Extensive machining for flow spun domes. Bonding operation & NDE would be difficult. Inverted weld to barrel more difficult & weld tooling more complex. Siphon feed line thru barrel requires forged panel. Vertical assy/high bay required for final tank/tank assy. Minimum of 3 dome assys required for development, test, & cutup.

Operational Complexity

- Separate Domes Provide Access to Intertank for Easier Checkout/Tests
- Easier Propellant Loading (Less Monitoring/Pressurization Concerns) for Separate Domes

Weight

- Dome & intertank weight savings of 4332 lbs/LRB for common bulkhead

Reliability

- Common bulkhead less reliable due to mfg/operational complexity.

S-1 Common Bulkhead Trade Summary (Cont'd)

Safety

- Separate domes provide inspection space & make purging & hazardous gas detection easy. Single leak in either dome is not catastrophic. Tanks can be loaded or pressurized independently. Tanks can be separated for proof testing & all surfaces available for inspection.
- Common domes provide no access for inspection. Purging & haz gas detection require nested domes separated by permeable material. Tanks must be connected for proof testing & dome is accessible only by entering tank which prohibits quick egress if flaw is detected. Strict loading & pressurization sequence is required to assure dome pressure differences.

Supportability

- Separate domes require less training of maintenance personnel, more accessibility, and less operational impacts.

Performance

- The weight penalty of 4332 lbs/LRB creates a payload penalty of 1300 lbs/flt for separate domes.
- The reduction in length creates less overall drag which results in a payload gain of about 750 lbs for the common dome configuration.
- Net Performance Loss of 550 lbs/flight

SEPARATE DOMES FOR LRB

LRB Trade Studies Plan

Discipline: Structures

Trade No: S-2

Title: Forward LRB ET/Attachment

Baseline: Crossbeam

Candidates: Ring Frame

Selection Criteria:

Criteria	Weighting Factor	Crossbeam		Ring Frame	
		Score	Weighted Score	Score	Weighted Score
Costs	40	10	400	8	320
Manufacturing Complexity	40	10	400	6	240
Weight	10	10	100	9	90
Supportability	10	10	100	7	70
	100		1000		720

S-2 FWD LRB/ET Attachment Summary

<u>Costs</u>

- Material Costs Are Lower for Crossbeam
- Ring Frame Construction More Labor-Intensive - i.e., Inspections,Barrel Build-up & Beam Alignment
- Additional Tooling Required for Ring Frame

<u>Manufacturing Complexity</u>

- Crossbeam Similar to ET Experience, Beam Configuration Allows for Easier Alignment & Beam Buildup, Single Wall Barrel with Frames Requires Uncomplicated Tooling & Assy Processes
- Ring Frame Requires Complex Tooling & Assy Methods, Material Thicknesses Require Weld Tooling & Fixturing, Ring Alignment Requires More Complex Assy Techniques & Tolerance Measurements

<u>Weights</u>

- Crossbeam - 3171 lbs (2 Frames)
- Ring Frame - 3747 lbs

<u>Supportability</u>

- Crossbeam Requires Less Time for Processing & Less Maintenance

FWD LRB/ET ATTACHMENT SHOULD BE A CROSSBEAM

LRB Trade Studies Plan

Discipline: Structures

Trade No: S-3

Title: Dome Optimization (Press-Fed Only)

Baseline: Elliptical

Candidates: Spherical

Selection Criteria:

Criteria	Weighting Factor	Elliptical Dome		Spherical Dome	
		Score	Weighted Score	Score	Weighted Score
Costs	30	8	240	10	300
Manufacturing Complexity	15	8	120	10	150
Weight	15	6	90	10	150
Supportability	10	8	80	10	100
Performance	15	8	120	10	150
Design Complexity	15	10	150	5	75
	100		800		925

S-3 Dome Optimization Summary

Costs

- Dome Tooling is Easier/Less Complex for Hemispherical - 25%
- Hemispherical Reduces Material Requirements
- Non-Recurring - $4,726K, Recurring - $9,659K Savings for Hemispherical Domes

Manufacturing Complexity

- Recurring Complexities Are Very Close With Slight Edge to Hemispherical for Ease of Fit of Dome Panels & Operations Involving Feed Thru Fittings.

Weight

- Hemispherical Is Heavier than Tapered Elliptical - 81 lbs/dome * 3 domes/LRB = 243lbs/LRB
- Hemispherical Adds Intertank Weight of 297 lbs/Dome * 2 Domes = 594 lbs/LRB
- Elliptical Adds Cylinder Weight of 1298 lbs/Cylinder * 3 Cylinders = 3894 lbs/LRB
- Total Weight - Hemispherical Domes Save 3057 lbs/LRB

Supportability

- Hemispherical Domes Require Less Processability & Supportability with More Access

Performance

- Weight Savings of 3057 lbs/LRB for Hemispherical = 917 lbs Payload/Flt
- Increased Length Due to Hemispherical Domes of 30" Creates Extra Drag which Reduces Payload Capability about 337 lbs
- Net Payload Increase of 580 lbs/flight

Design Complexity

- Problems with Crossbeam & Pressurization Tank Placement
- May Require Increasing Length

HEMISPHERICAL DOMES FOR PROPELLANT TANKS

LRB Trade Studies Plan

Discipline: Structures

Trade No: S-4

Title: Unpressurized Structure Construction

Baseline: Hat Stiffened

Candidates: Monocoque, Z-Stiffened, Waffle, Truss Core

Selection Criteria:

Criteria	Weighting Factor	Hat Stiffened		Monocoque		Z-Stiffened		Waffle		Truss Core	
		Score	Wghted Sc	Score	Wghted Sc	Score	Wghted Sc	Score	Wghted Sc	Score	Wghted Sc
Costs	30	10	300	9	270	9	270	5	150	2	60
Manufacturing Complexity	30	8	240	10	300	7	210	5	150	4	120
Weight	20	8	160	5	100	9	180	9	180	10	200
Supportability	10	6	60	10	100	7	70	6	60	6	60
Performance	10	8	80	6	60	9	90	9	90	10	100
	100		840		830		820		630		540

S-4 Unpress. Structure Construction Summary

<u>Costs</u>

- Hat & Z Stiffened Concepts Have Lowest Material Costs
- Material Preparation Costs Increase for Truss & Waffle Construction
- Tooling Costs Are Lowest for Hat Stiffened & Monocoque, Worst for Truss
- Labor Costs Are Best for Monocoque & Worst for Truss
- DDT&E Costs Are Very High for Truss Construction Due to Increased Test Article Rqts

<u>Manufacturing Complexity</u>

- Monocoque - Simple Non-Specialized Operations at Each Step
- Hat-Stiffened - Mechanically Fastened, No Specialized Operations
- Z-Stiffened - Alignment of Z Stiffeners More Difficult, Requires Additional Tooling
- Waffle - Time Consuming Machining on Waffle Grid, Difficult Forming, Weld Tooling More Dificult
- Truss - Mech. Assy Requires Blind Rivets, Difficulty in Sizing Diameter of Structure, Development Articles Required, Risk Higher

<u>Weight</u>

- Intertank Weight (lbs) Δs : Truss - 0, Waffle - 1128, Z-Stiff - 1231, Hat Stiff - 1642, Mono - 3283

<u>Supportability</u>

- Monocoque Requires Least Amount of Processing & Maintanance Time, All Other Candidates Are About Equal

<u>Performance</u>

- Weight Δs Result in Performance Penalties Up to About 1000 lbs /Flt

HAT STIFFENED SHOULD BE THE UNPRESSURIZED STRUCTURE CONSTRUCTION METHOD

LRB Trade Studies Plan

Discipline: Structures

Trade No: S-5

Title: Cryogenic Tank Location

Baseline: Cryogenic Tank Forward

Candidates: Cryogenic Tank Aft

Selection Criteria:

Criteria	Weighting Factor	Cryo Tank Forward		Cryo Tank Aft	
		Score	Weighted Factor	Score	Weighted Factor
STS Integration Impacts	20	10	200	5	100
Costs	15	10	150	9	135
Performance/Stability	15	10	150	8	120
Launch Facilities/Ground Impacts	10	7	70	10	100
Operational Complexity	10	7	70	10	100
Weight	10	10	100	8	80
Reliability	5	10	50	6	30
Technical Risks	10	10	100	7	70
Schedule Risks	5	10	50	8	40
Totals	100		950		775

S-5 Cryogenic Tank Location Summary

STS Integration Impacts

- Aft Cryo Tanks Overload Aft LRB Attach Hardware & ET - Requires Revision to ET 2058 Frame & Interface Hardware
- MLP Tie-Down Loads Increase for Aft Location - Requires Revision to MLP Tie-Down Pedestals
- Dynamic Twang Loads Increase for Aft Location

Costs

- Cost Impacts to ET 2058 Frame for Aft Location - $991K Nonrecurring & $1848K Recurring

Performance/Stability

- ET Frame Weight Increase Reduces Performance by 600 Lbs
- Stability Not Changed by Either Location

Launch Facilities/Ground Impacts

- Umbilical Impacts (Fill & Drain) for Forward Tank Location
- Forward Location May Require Venting Umbilical on Tower
- Less Blast Protection Required for Forward Location

Operational Complexity

- Easier Access to Aft Tank for TPS Closeouts, Contingencies, Etc.
- Aft Tank Location Minimizes Ice Debris Problems

Weight

- Aft Tank Location Increases Weight of ET 2058 Frame by 600 Lbs
- No LRB Weight Impacts

S-5 Cryogenic Tank Location Summary (Cont'd)

Reliability

- Reliability of Aft Tank Location Decreases Due to Structural Load Concerns

Technical Risks

- Technical Risks of Aft Tank Location Increases Due to Structural Load Concerns
- Forward Tank Location Increases Risks of Ice Debris Problems

Schedule Risks

- Schedule Risks Increase with Mods to ET Frames and Interface Hardware

IF ONLY ONE OF THE PROPELLANT TANKS CONTAINS CRYOGENS,
IT SHOULD BE THE FORWARD TANK OF THE LRB.

LRB Trade Studies Plan

Discipline: Structures

Trade No: S-6

Title: Tank Wall Design (Pump Only)

Baseline: Machined Integral Stiffeners

Candidates: Thick Wall (Monocoque)

Selection Criteria:

Criteria	Weighting Factor	Thick Wall		Machined Integral Stiffeners	
		Score	Weighted Score	Score	Weighted Score
Costs	30	10	300	3	90
Manufacturing Complexity	20	10	200	6	120
Weight	20	6	120	10	200
Performance	20	5	100	10	200
Supportability	10	10	100	8	80
	100		820		690

S-6 Tank Wall Design Summary

Costs

- Integral Stiffeners Requires 6 Times More Material, 4.5 Times More Machining, & Twice the Labor; Design Costs Less for Monocoque
- Stiffeners Non-Recurring - $8,042K More than Monocoque
- Stiffeners Recurring - $217,123K More than Monocoque
- No Costs Deltas Developed for Impacting Flight Weight & Engine Thrust Rqts

Manufacturing Complexity

- Monocoque - No specialized operations, no in tank installations required on ring frames, tooling is less complex.
- Stiffeners - 6" pitch requires large amount of machining time and 2" cap forming will be difficult, age forming required to achieve good contour, development required, internal weld tool more complex, requires installation of intermediate barrel frames after welding.

Weight

- Monocoque Skin - 7.2 lbs/ft2 - 26,830 lbs tanks weight.
- Stiffeners - 4.5 lbs/ft2 - 17,100 lbs tank weight.
- Δ Weight Savings of 9,730 lbs/LRB for Stiffeners
- More Design Costs for Integral Stiffeners

Performance

- Weight penalty of 9,730 lbs/LRB for monocoque = 2919 lbs/flt performance penalty.

Supportability

- Stiffeners require more processing time for reinspection, more maintenance training and support, and more accessibility and task complexity.

THE TANK WALL DESIGNS SHOULD BE THICK WALL (MONOCOQUE)

LRB Trade Studies Plan

Discipline: Structures

Trade No: S-8A

Title: Materials Trades (Pressure-Fed)

Baseline: Weldalite

Candidates: 2219, 2090, HP 9-4-30

Selection Criteria:

Criteria	Wgting Factor	Weldalite		2219		2090-T8E41		HP 9-4-30	
		Score	Wgt Score	Score	Wgt Score	Score	Wgt Score	Score	Wgt Score
Costs	10	2	20	3	30	2	20	10	100
Performance	20	10	200	1	20	8	160	2	40
Manufacturing Complexity	20	6	120	10	200	5	100	8.5	170
Weight	20	10	200	1	20	8	160	1	20
Technical Risks	10	9	90	10	100	9	90	7	70
Schedule Risks	10	9	90	10	100	9	90	9	90
Safety	10	8	80	10	100	7	70	10	100
	100		800		570		690		590

S-8A Materials Trade (Pressure-Fed) Summary

Costs

- Welding Labor Costs Driven by Thick Aluminum Construction - 6.5 Times Thicker Wall than Steel
- Raw Material Costs for 2219 Is Half of that for Any Other Option
- Large Tooling Impact for Aluminum Construction Due to Thickness of Welds Required

Weights

- Structural Weight Δs (lbs) : Weldalite - 0, 2219 - +72,610, 2090 - +25,610, HP 9-4-30 - +65,670
- Weights Affect Performance & Engine Size

Performance

- Performance Penalties/Flight (lbs) Based On Weight Δs: Weldalite - 0, 2219 - 21,783, 2090 - 7,683, HP 9-4-30 - 19,701

Manufacturing Complexity

- Limited Welding Experience for Weldalite which Requires Welding Development
- 2219 Rates High in All Aspects Due to Past Uses on ET
- 2090 Rates Low in Weldability & Requires Welding Development

Technical & Schedule Risks

- 2219 Is Proven Material with No Technical & Schedule Risks
- Weldalite Has a 95% Probability of Being Developed Adequately by 1992
- 2090 Is Still Experimental Posing Some Technical & Schedule Risks
- HP 9-4-30 Is a New Alloy & Has Been Produced Only in Bar Stock, Heat Treatment Problem

Safety

- 2219 Has Well Known Properties & Large Body of Test Data
- HP 9-4-30 Rates Well for Weldability,Fracture Toughness, & Heat Treatment
- Molten Al-Li Alloys with 2% Li Have Caused Explosions in Testing (Weldalite-1.3%, 2090-2%), Concentrations of 1.2% Did Not Explode; Al-Li Scrap Must Be Segregated from Other Al Scrap

WELDALITE SHOULD BE THE MATERIAL FOR PRESSURE-FED LRB

LRB Trade Studies Plan

Discipline: Structures

Trade No: S-8B

Title: Materials Trades (Pump-Fed)

Baseline: Weldalite

Candidates: 2219, 2090, HP 9-4-30

Selection Criteria:

Criteria	Wgting Factor	Weldalite		2219		2090-T8E41		HP 9-4-30	
		Score	Wgt Score	Score	Wgt Score	Score	Wgt Score	Score	Wgt Score
Costs	10	9.5	95	10	100	9.5	95	6	60
Performance	20	10	200	6	120	9	180	2	40
Manufacturing Complexity	20	6.5	130	10	200	6	120	7	140
Weight	20	10	200	6	120	8	160	1	20
Technical Risks	10	9	90	10	100	9	90	7	70
Schedule Risks	10	9	90	10	100	9	90	9	90
Safety	10	8	80	10	100	7	70	10	100
	100		885		840		805		520

S-8B Materials Trade (Pump-Fed) Summary

<u>Costs</u>

- 2219 Material Is Half Cost of Any Other Option
- Recurring Labor Rqts Increase for HP 9-4-30 Due to Thin Material

<u>Weights</u>

- Structural Weight Δs (lbs) : Weldalite - 0, 2219 - +8,300, 2090 - +2,230, HP 9-4-30 - +22,075
- Weights Affect Performance & Engine Size/Thrust

<u>Performance</u>

- Performance Penalties/Flight (lbs) Based On Weight Δs: Weldalite - 0, 2219 - 2,490, 2090 - 669, HP 9-4-30 - 6,623

<u>Manufacturing Complexity</u>

- Limited Welding Experience for Weldalite Requires Welding Development
- 2219 Rates Relatively High in All Aspects Because of Past Uses on ET
- 2090 Rates Low in Weldability & Requires Welding Development
- HP 9-4-30 for Small Wall Thicknesses Presents Fixturing & Handling Problems

<u>Technical & Schedule Risks</u>

- 2219 Is Proven Material with No Technical & Schedule Risks
- Weldalite Has a 95% Probability of Being Developed Adequately by 1992
- 2090 Is Still Experimental Posing Some Technical & Schedule Risks
- HP 9-4-30 Is a New Alloy & Has Been Produced Only in Bar Stock, Heat Treatment Problem

<u>Safety</u>

- 2219 Has Well Known Properties & Large Body of Test Data
- HP 9-4-30 Rates Well for Weldability,Fracture Toughness, & Heat Treatment
- Molten Al-Li Alloys with 2% Li Have Caused Explosions in Testing (Weldalite-1.3%, 2090-2%), Concentrations of 1.2% Did Not Explode; Al-Li Scrap Must Be Segregated from Other Al Scrap

WELDALITE SHOULD BE THE MATERIAL FOR PUMP-FED LRB
2219 ALUMINUM REMAINS A CLOSE BACKUP

LRB Trade Studies Plan

Discipline: Structures

Trade No: S-9

Title: Aft Skirt & Tie Down Attach

Baseline: Skin/Stringer Attach

Candidates: Monocoque

Selection Criteria:

Criteria	Weighting Factor	Skin/Stringer Attach		Monocoque	
		Score	Weighted Score	Score	Weighted Score
Costs	20	10	200	9	180
Manufacturing Complexity	30	10	300	8	240
Weight	20	10	200	6	120
Supportability	10	6	60	10	100
Performance	20	10	200	8	160
	100		960		800

S-9 Aft Skirt & Tie Down Summary

Costs

- Monocoque Requires Milling for Weld Lands
- Additional Tooling Is Required for Monocoque
- Additional Floor Space Required which Increases Facility Costs

Manufacturing Complexity

- Monocoque - Complex Weld Tools & Procedures, Tapered Welds Required at Longeron Connections Cause Weld Defects, Inspection Required, Trim Station after Welds, Final I/Fs on Sections Require Trimming on Boring Mill
- Skin/Stringer - Less Complex Tooling, Inspection Less Stringent, Tolerances More Easily Obtained

Weight

- Monocoque - 18430 lbs
- Skin/Stringer - 13170 lbs

Performance

- Monocoque Weight Penalty of 5260 lbs Equals a Payload Penalty of 1578 lbs/flight

Supportability

- Skin/Stringer Requires More Maintenance & Training and Has Greater Task Complexity

SKIN/STRINGER CONSTRUCTION FOR AFT SKIRT & TIE DOWN

LRB Trade Studies Plan

Discipline: Structures

Trade No: S-10

Title: Filament Wound Composite Tank (Pressure Only, Non-Cryo)

Baseline: Welded Construction (Weldalite)

Candidates: Filament Wound Composite (Gr/Peek) , Composite (Gr/Peek) Overwrapped Aluminum

Selection Criteria:

Criteria	Weighting Factor	Welded		Filament Wound		Composite Overwrap	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Costs	15	7	105	10	150	2	30
Manufacturing Complexity	15	6.5	98	10	150	5	75
Weight	15	4	60	10	150	7	105
Safety	15	10	150	1	15	1	15
Reliability	10	10	100	5	50	8	80
Technical Risks	10	10	100	3	30	2	20
Supportability	10	10	100	7	70	7	70
Performance	10	5	50	10	100	8	80
	100		763		715		475

S-10 Filament Wound Composite Tank Summary

<u>Costs</u>

- Raw Material Costs Comparable; Weldalite & Overwrap Have Higher Milling & Assy Labor Costs
- More Tooling Needed for Overwrap; More Test Rqts for Composites; Liner Material & Application Costs Are TBD

<u>Manufacturing Complexity</u>

- Welded - Lab Welds Only with Weldalite, Large Vertical Weld Fixtures, More Processing Steps
- Filament Wound - Limited Experience Winding Vessels this Large, Liner Unproven
- Overwrap - Same as Filament Wound, Reduced Mandrel Rqt, More Processing Steps

<u>Weight</u>

- Weldalite - 135,780 lbs, Filament Wound (Gr/Peek) - 107,108 lbs, Overwrap - 117,386 lbs

<u>Safety</u>

- Welded - Proven & Reliable
- Filament Wound Structures - Additional Safety Effort Required to Verify Structural Parameters, Carbon Fibers Are Skin & Lung Hazard & Require Special Handling Techniques at Manufacturer, Graphite/Epoxy Safety Scores Would Be Higher than Graphite/Peek

<u>Reliability</u>

- Filament Wound - Lower Because of Technical Risk

<u>Technical Risks</u>

- Mfg Consolidation of Composite (Gr/Peek) w/o Autoclave Is Problem, Scale Up to Large Diameters Is Major Technology

<u>Supportability</u>

- Composites Require More Processing Time, Maint. Training, & More Maint. Complexity

<u>Performance</u>

- Wgt Penalty for Weldalite Means Payload Penalty of 8600 lbs/flight
- Wgt Penalty for Overwrap Means Payload Penalty of 3100 lbs/flight

WELDALITE WELDED CONSTRUCTION REMAINS BASELINE
GRAPHITE/EPOXY TANK CONSTRUCTION WILL BE STUDIED DURING PHASE II